Core Characterization of Patterson #5-25 Well for Carbon Capture and Storage in Western Kansas

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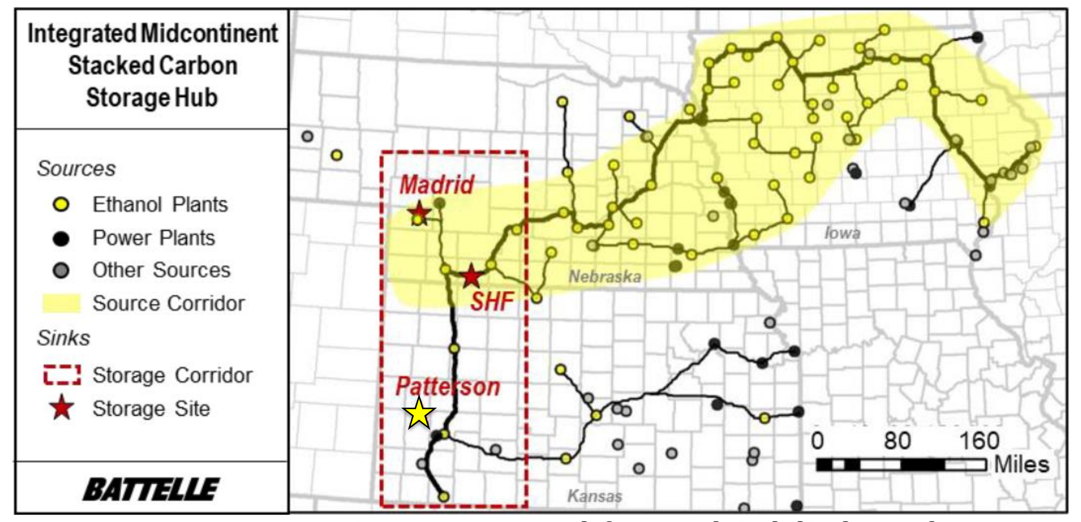
Abstract

The computed tomography (CT) facilities and the Geotek Multi-Sensor Core Logger (MSCL) at the National Energy Technology Laboratory were used to collect data and characterize core from the Patterson #5-25 well. The Patterson #5-25 well was drilled as part of the Kansas Geological Survey-led Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Phase 2 project, the Integrated Midcontinent Stacked Carbon Storage Hub (IMSCS-HUB). As part of the CarbonSAFE project, permeability measurements of selected core were measured in zones of interest. Beyond the initial project work, the lithology was characterized utilizing non-destructive qualitative (multi-scale CT images) and quantitative (X-ray fluorescence, P-wave velocity, gamma density, magnetic susceptibility) techniques to better characterize the reservoir quality and seal potential within the cored intervals. The core from the Patterson #5-25 well includes nearly 625 ft of core intermittently between the Pennsylvanian Atoka Shale and into the Precambrian Basement. Core logger data and coarse resolution CT images were taken from 2/3 slab core along the entire length of the core. In addition to this macroscopic characterization of the core, potential reservoir facies along the length were examined at ten locations with high-resolution CT images to examine reservoir pore systems and structural properties, such as fractures. The Pennsylvanian Morrow Sandstone and Cambrian Reagan Sandstone had the best reservoir quality with high porosity and permeability. The Pennsylvanian Atoka Shale had the best seal potential with low permeability and few fractures. Throughout the Cambro-Ordovician Arbuckle Group, zones of good reservoir conditions via secondary porosity were observed, with intervals of sub-mm to cm-scale vuggy porosity separated by relatively tight dolomitic zones. The Meramecian, Osage, and Viola carbonate units were observed to have generally thinner zones of good reservoir quality with some small baffles.

Site Background:

The IMSCS-HUB was designed to develop a commercial-scale carbon capture, utilization, and storage project as part of a Phase CarbonSAFE project. The IMSCS-HUB is made up of ethanol, power plants, and other sources in Iowa, Kansas, and Nebraska, and three stacked storage corridors: Sleepy Hollow Field (southwest-central Nebraska), Madrid (southwest Nebraska), and Patterson Site (Patterson, Heinitz, Hartland, and Oslo fields). The Patterson #5-25 well is the focus of this study and is shown in the gold star in the map on the right.



IMSCS HUB site map; Gold star highlights the Patterson [1]

The Patterson #5-25 well has 625 ft of core from the Atoka to the Precambrain Basement. The table to the left shows the cored intervals and the dominant lithology.

Cored intervals in the Patterson 5-25 well

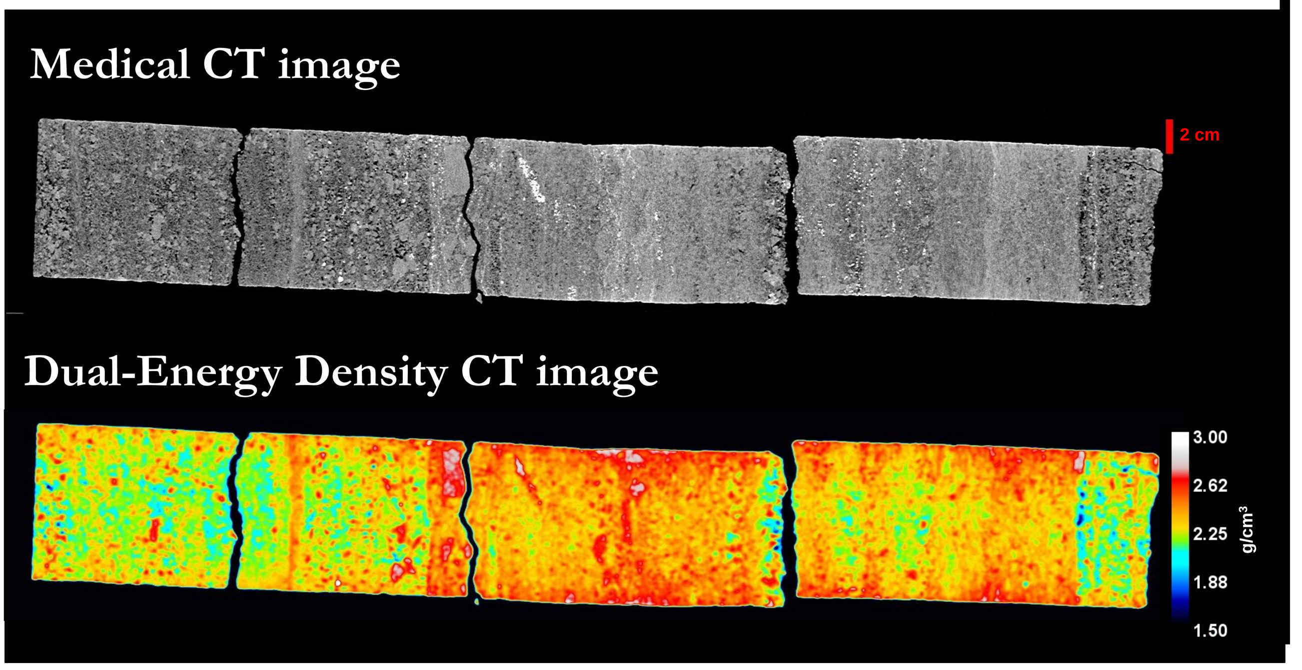
Group/Formation	Cored depth (ft)	Primary lithology
Atoka Stage	4,615 to 4,751	Shale
Morrowan Stage (Morrow Sand)	4,751 to 4,880	Mixed (sand, shale, limestone)
Meramecian Stage	4,880 to 4,957	Limestone
Osage Stage	5,380 to 5,439	Limestone
Viola Formation	5,640 to 5,719	Limestone
Upper Arbuckle (Jefferson City- Cotter Fm.)	5,780 to 5,826	Dolomite
Lower Arbuckle (Roubidoux Fm and Bonneterre Fm.)	5,959 to 6,200	Dolomite
Reagan Sandstone and Granite Wash	6,214 to 6,273	Sandstone
Precambrian Basement	6,278 to 6,300	Granite

Data Collection:

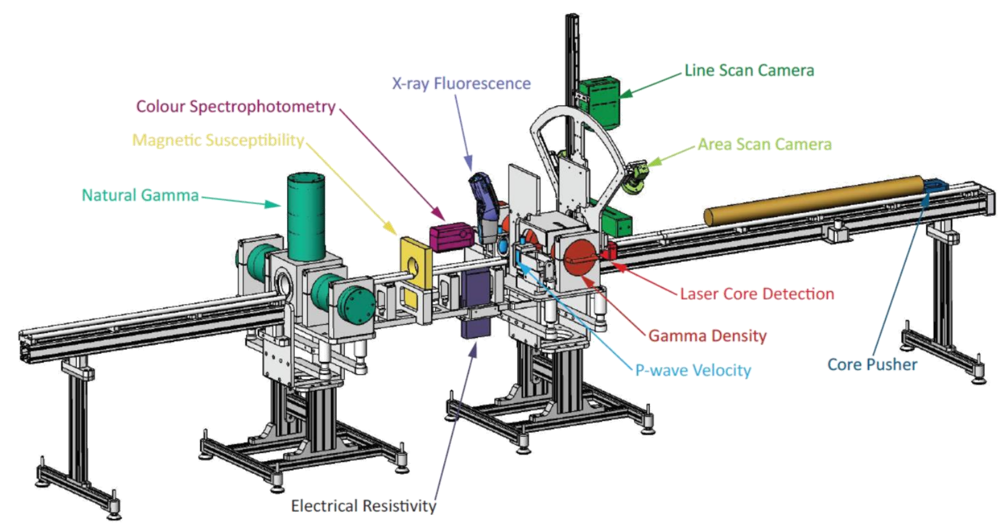
Medical CT-images

NETL's Toshiba® Aquilion RXL™ Multislice Helical CT Scanner

- Voxel resolution of 0.43 x 0.43 mm in the XY plane and 0.50 mm along the core axis.
- Important for identification of zones of interest for more detailed analysis, experiment, and quantification.
- Density variation is calculated using dual energy scans. See example below.



Geophysical Logging MSCL

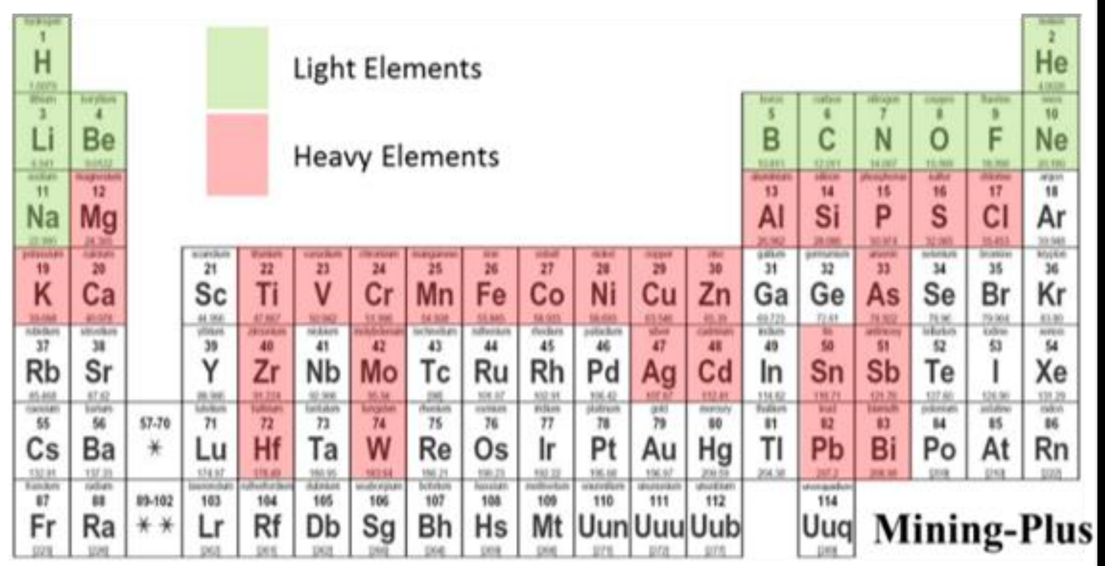


X-Ray Fluorescence (XRF) Elemental Suite:

XRF was measured using a handheld Delta Innov-X® X-Ray Fluorescence Spectrometer

Mining-Plus:

- 2-beam analysis, 60 s exposure time
- Major and transition elements (some trace)



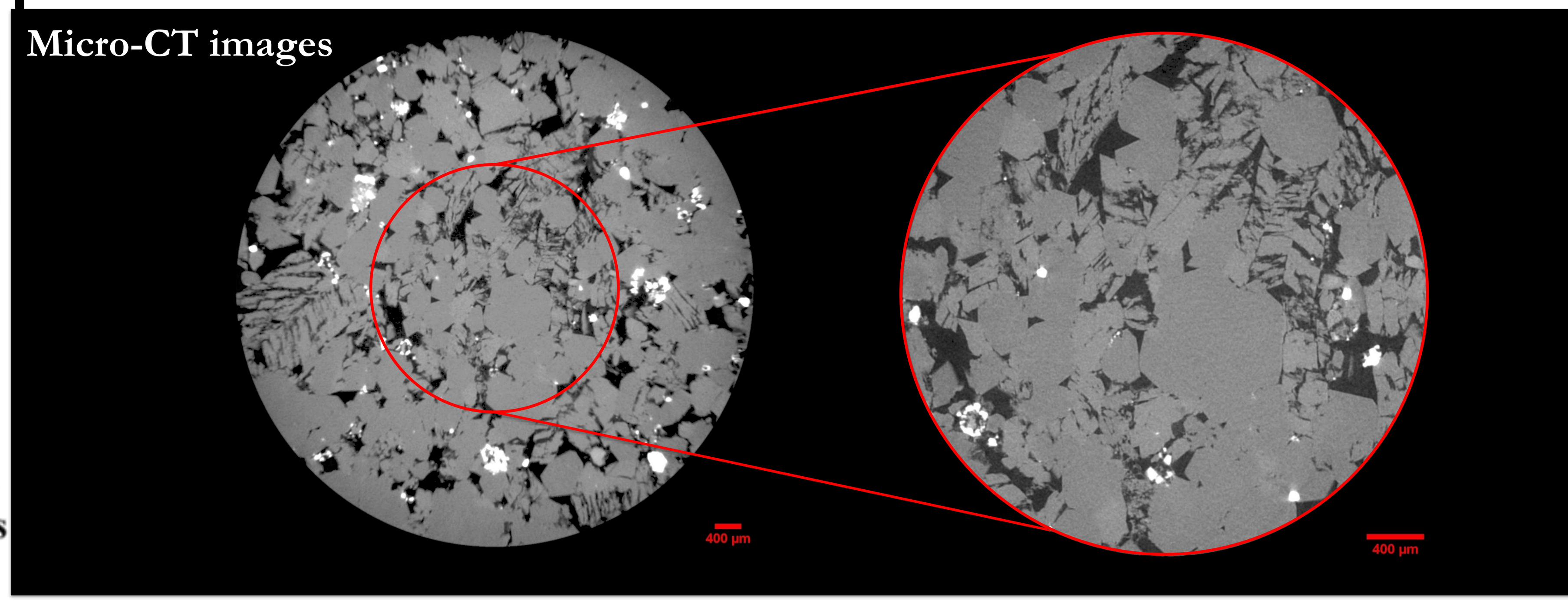
Micro-CT Images

NETL's ZEISS Xradia MicroXCT-*400* Scanner

- The highest resolution of the scanners at NETL
- Scans samples sized from sub-mm to 25 mm
- Provides detailed image data that can be used to infer porosity, mineralogy, and structure
- Below are two examples of micro-CT images from 6.266 ft in the Granite Wash

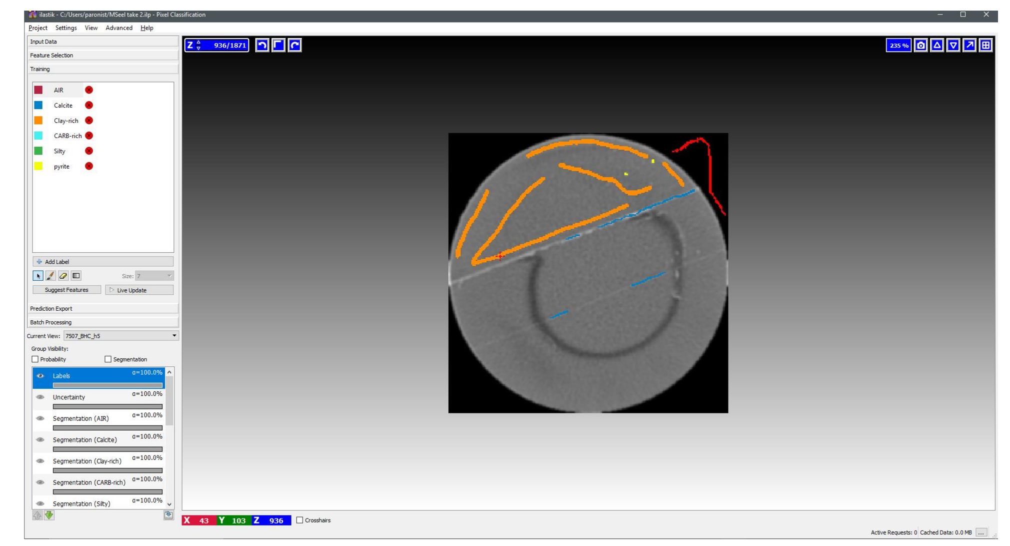
Micro-CT samples in the Patterson 5-25 well

Depth (ft)	Formation	Resolution (µm³)
4,771.30	Morrow Sand	1.87
5,812.40	Upper Arbuckle/ Jefferson City- Cotter Fm	1.87
5,972.12	Lower Arbuckle/Roubidouix Fm.	1.87
6,213.50	Bonneterre-Reagan Sand Boundary	1.87
6,222.60	Reagan Sand	1.87
6,222.60	Reagan Sand	6.05
6,266.15	Granite Wash	1.87
6,266.15	Granite Wash	3.95

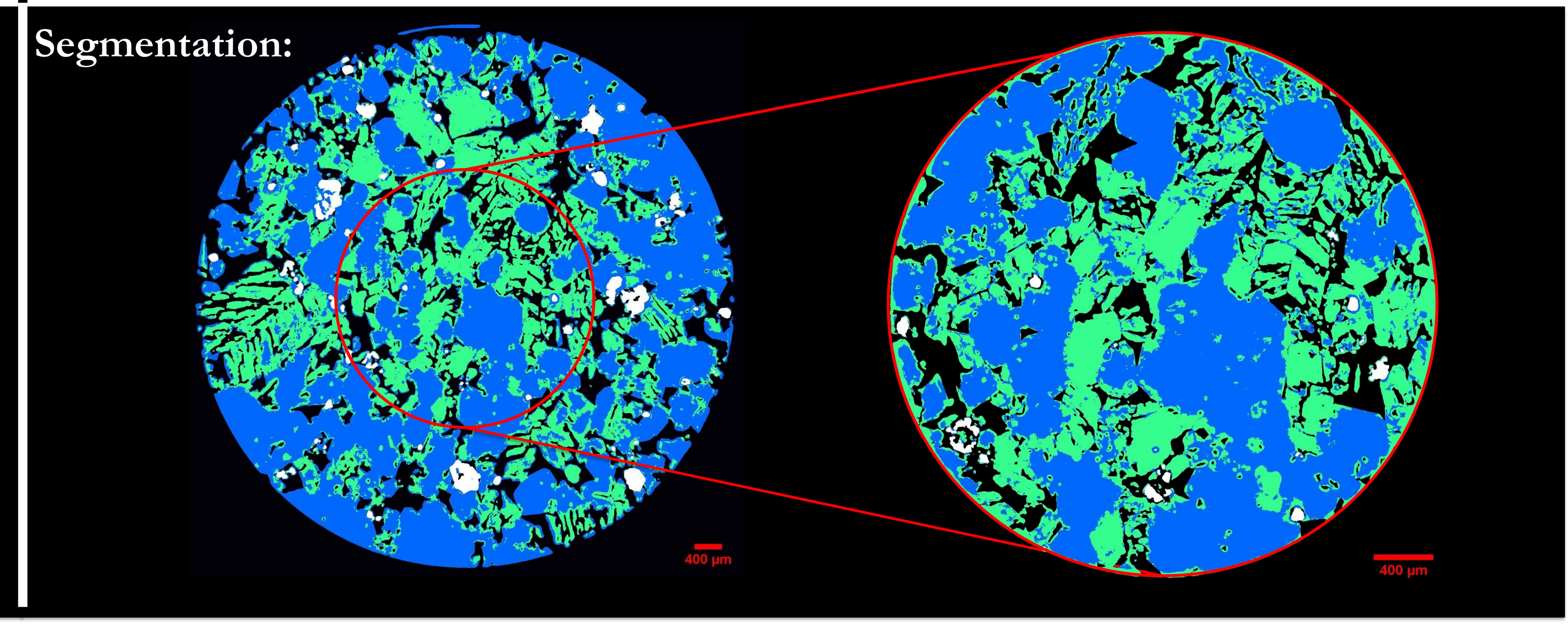


ilastik Segmentation

- Ilastik is a supervised machine learning software that utilizes user training to determine feature classes based on a feature vector: color/intensity, edge type, and texture [2] (example on the right).
- Images are pre-processed with a 2-sigma 3D Gaussian Blur and normalizing gray-scale levels.



- Seven sample were analyzed (shown in the micro-CT table); both the higher and lower resolution scans from the Reagan Sand and Granite Wash were analyzed.
- Sample volumes were sub-voluemd into 500x500x500 pixel volumes for training in ilastik, and the final volume was processed from this training set. This allows for:
  - mitigating edge effects of beam hardening in the whole volume
  - limits memory error and slow loading times
- Segmented images were brought back into ImageJ where a Look Up Table was applied to highlight the feature classes, and a histogram was calculated to show the distribution of feature classes within a Region of Interest (ROI) and subsequently give the porosity for the sample based on the percent of air within the sample.



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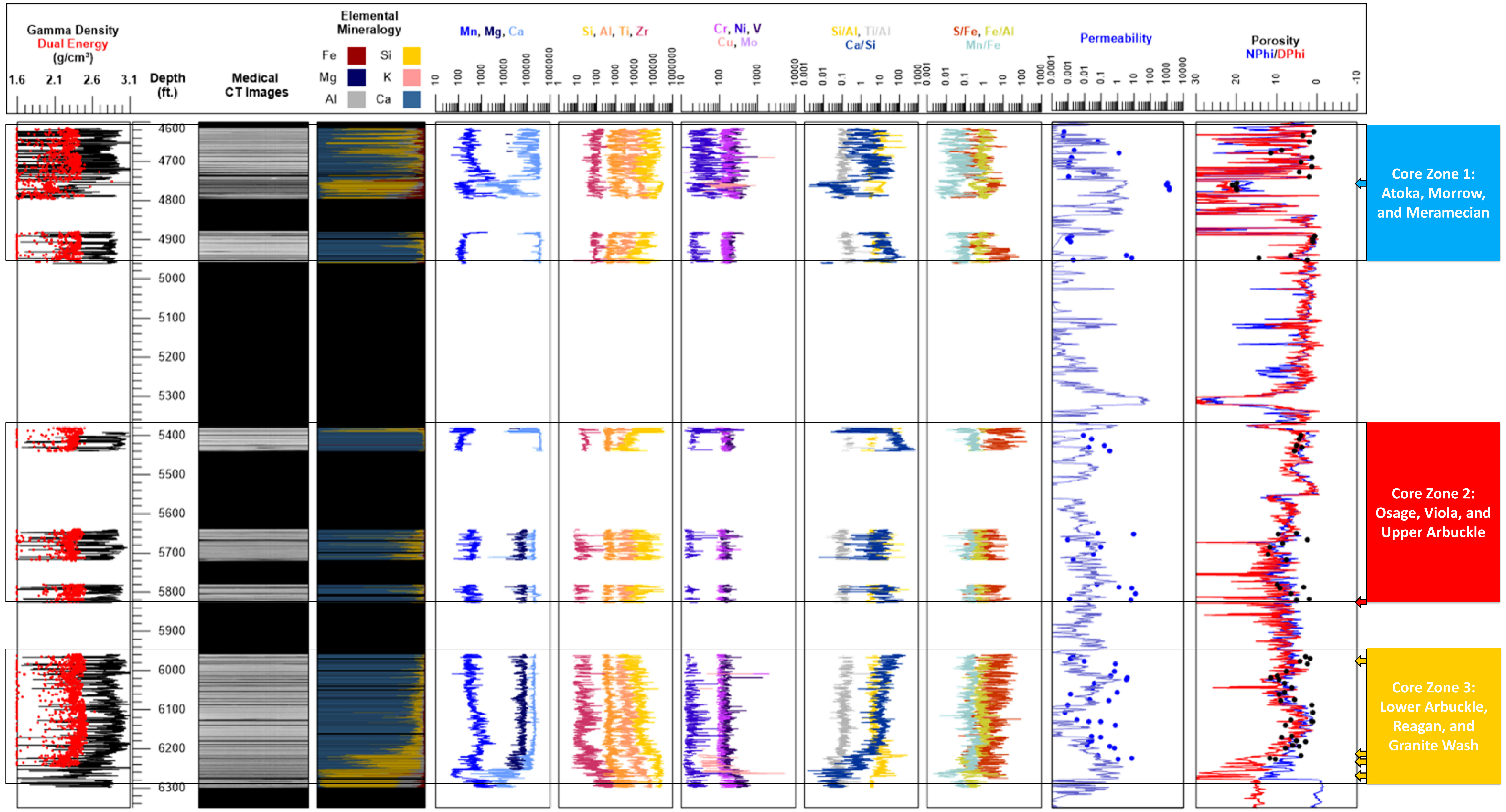
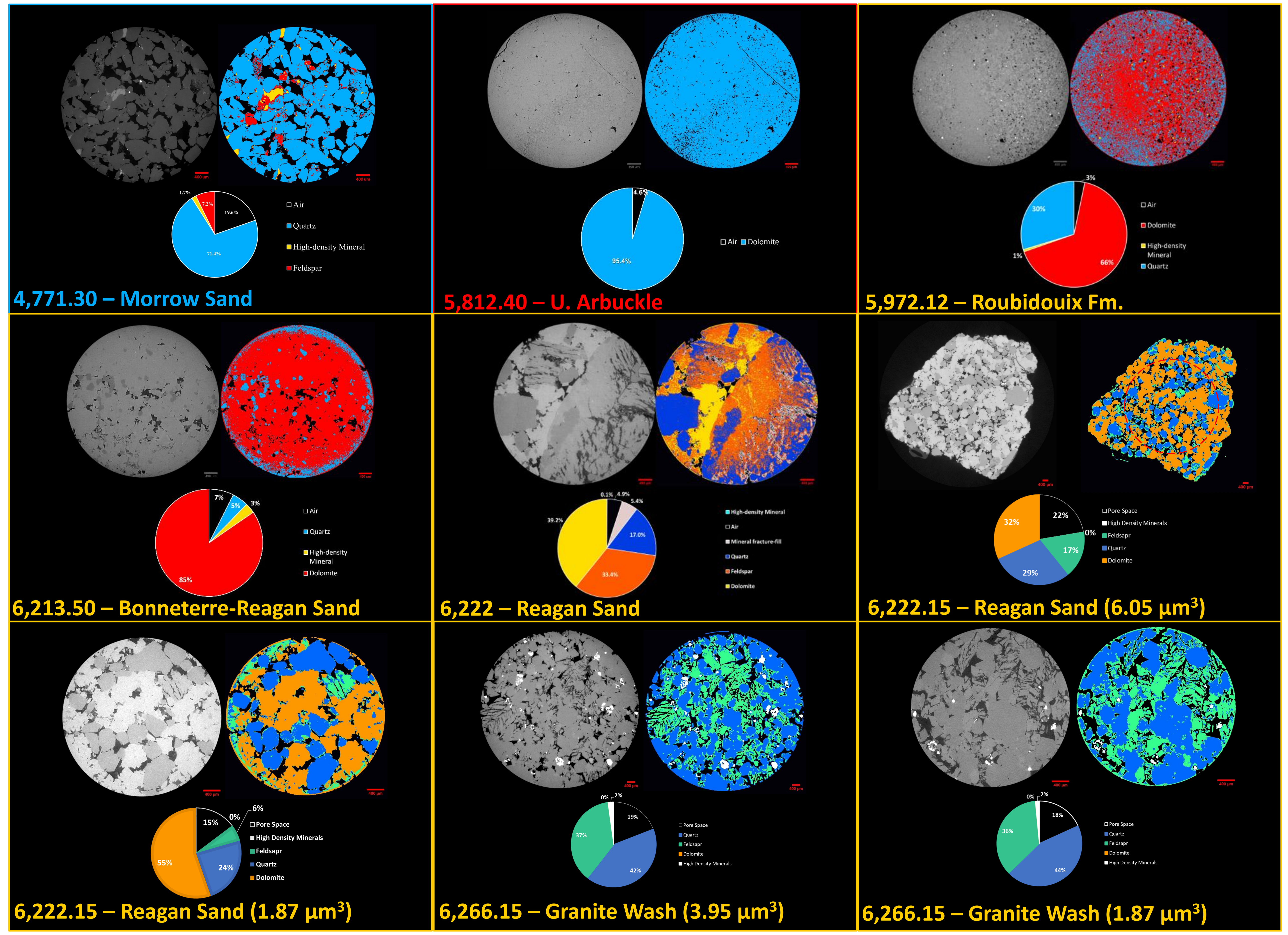
Core Characterization Results: MSCL and Medical CT Data



Log plot showing the results of the MSCL and Medical CT images, Column 1 represents gamma density (black) and dual energy density (red, 1 every 20 points); Column 2, medical CT images; Column 3, elemental mineralogy; Column 4, carbonate/skeletal influx proxies; Column 5, detrital proxies; Column 6, redox proxies; Column 7, detrital proxy ratios; Column 8, redox proxy ratios; Permeability (Coates from NMR, blue line; Core derived, blue dots); Column 10, Porosity (neutron porosity (Nphi, blue line), density porosity (DPhi., red line), core derived (black dot). Arrows denote the location of subcores used in ilastik segmentations.

ilastik Segmentation



Discussion:

Zone 1:

Zone 1, Atoka, Morrow, and Meramecian, is made up primarily of sandstone, shale, and limestone. The Atoka stage rocks are made up of interlayered shales, mudstones, and wackestones. It has general low porosity and permeability. The Morrow Sand has high permeability and porosity throughout the cored section. The sand is made up of primarily quartz with minor amounts of muscovite and feldspar. The Meracmecian Stage strata is made up of limestone; primarily mudstone, but some intervals of conglomerate and vugs, which correlate with an increase in the S/Fe ratio.

Zone 1 had one segmentation: results of the ilastik threshold; a sample composition with 71.4% quartz, 7.2 % feldspar, and 1.7% high-density minerals (including dolomite/calcite), with a porosity of 19.6%. Some muscovite was present, but was very minor and not included in the segmentation.

Zone 2:

Zone 2, Osage, Viola, and Upper Arbuckle, is made up primarily of carbonate rocks, limestone in the Osage, and dolomite in the Viola and Upper Arbuckle. This interval has generally low porosity and permeability, except for a sandy interval in the Osage and some vuggy intervals in the Viola and Upper Arbuckle.

Zone 2 had one segmentation in the Upper Arbuckle around a vuggy interval with pin-point porosity. The sample is made up almost entirely of dolomite with some pore space and open fracture (4.7%) and a very minor amount of high-density minerals.

Zone 3:

Zone 3 includes the Lower Arbuckle, Reagan, and Granite Wash. The Lower Arbuckle is made up primarily of dolomite, and the Reagan and Granite Wash are made up of sand. Generally, the dolomitic sections of Zone 3 have low porosity and permeability, except for some vug-rich intervals and some thin sands at the base of the Roubidoux and Bonneterre formations. There were 5 samples segmented including 2 at varying resolutions. Through these samples and in the logs, porosity and permeability increase toward the base of Zone 3 which corresponds to a decrease in dolomite and increase in sand. This can be seen in the segmentation results of the 5,972.12, 6,213, 6,222, and 6,266 samples, where dolomite dominant in the Roubidoux and Bonneterre-Reagan transition to 50/50 sand (quartz+feldspar) in the Reagan to a very minor amount in the granite wash.

The segmentation results between the higher and lower resolution scans of the same sample are dependent on the heterogeneity of the sample giving similar results in the Granite Wash, but not in the Reagan sands due to the presents of a few large feldspar grains in the volume.

Conclusions:

- Ilastik segmentation allows determination of mineralogy and porosity in a non-destructive manner. This method is limited by the time of analysis (scanning + training) but can be remedied by limiting the size of the training volumes and normalizing gray-scale values prior to training.
- Heterogeneous samples create a challenge in dealing with beam-hardening effects at the sample edge. The solution to this is to train the segmentation around the interior of the core where beam-hardening effects are minimized and create an ROI to ignore the areas where they are most prominent.
- Additionally, heterogeneity can cause some amount of sampling error particularly at high resolutions, such as in sample 6222.15.
- Future work includes: Pore morphology (pore size and connectivity), quantifying the pore space focusing on mineral contacts within the pore space important for wettability in CO_2 injection, and upscaling high-resolution data to log- and well-scale to understand and tie it to historical well data.
- All data associated with this experiment and all other core characterization efforts at NETL can be found following the QR code to the right.

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Acknowledgements and Disclaimer:

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All data in this project is available on EDX (https://edx.netl.doe.gov/group/core-characterization).
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Citations: **[1]** J. Walker, K. Smith, Integrated Mid-Continent Stacked Carbon Storage Hub Phase II, Final Summary Report, DOE Agreement/Project #DE-FE0031623, Battelle Project # 100122657. (2020); **[2]** S. Berg, D. Kutra, T. Kroeger, C.N. Straehle, B.X. Kausler, C. Haubold, M. Schiegg, J. Ales, T. Beier, M. Rudy, and K. Eren, Ilastik: Interactive machine learning for (bio) image analysis. Nature Methods, 16, 1-7 (2019); **[3]** Paronish, T.; Mitchell, N.; Schmidt, R.; Moore, J.; Brown, S.; Crandall, D.; Hasiuk, F.; Holubnyak, Y. E. Computed Tomography Scanning and Geophysical Measurements of the Patterson #5-25 Well in Western Kansas; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2022; p 84.